THE JPL Hg+ EXTENDED LINEAR ION TRAP FREQUENCY STANDARD: STATUS, STABILITY, AND ACCURACY PROSPECTS*

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Abstract

Microwave frequency standards based on room temperature $^{199}Hg+$ ions in a Linear Ion Trap (LITS) presently achieve a signal-to-noise and line-Q-inferred short-term frequency stability of $\sigma_y(\tau) = 2\times10^{-14}/\tau^{1/2}$. Long-term stability has been measured for averaging intervals up to 5 months with apparent sensitivity to variations in ion number/temperature limiting the flicker floor to about 5×10^{-16} at 100,000 seconds. A two-segment version of the linear ion trap (LITE) has also recently demonstrated excellent frequency stability for measurement intervals up to one week. Nearly an order of magnitude improvement in long-term stability compared to the LITS is expected since this trap configuration operates with reduced linear ion density during the microwave interrogation period.

INTRODUCTION

Mercury Linear Ion Trap frequency Standards (LITS) have been developed at JPL to address the practical needs of the NASA Deep Space Network (DSN) with the goal of providing frequency stability substantially better than the hydrogen masers currently in use in each DSN station. The DSN requires high-frequency stability for communication and tracking of a variety of spacecraft throughout the solar system. The stability needs vary from less stringent requirements for navigation, to more demanding requirements for very long baseline interferometry, gravity wave searches, and radio science experiments. Most recent frequency and timing stability requirements for the upcoming Cassini mission to Saturn are near 10^{-15} stability from 1 to tens of thousands of seconds. Frequency standards in the DSN must provide very high stability and operate continuously at remote locations from JPL. This requires the standards to be reasonably transportable, operate autonomously, and be very reliable.

THE LINEAR ION TRAP STANDARD (LITS)

The ongoing development of the LITS[1-5] based on the 40.5 GHz ground state hyperfine transition of ^{199}Hg ions[6] has recently led to the development of an engineering model for

*The work described here was performed by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 1996**	2. REPORT TYPE	3. DATES COVERED **00-00-1996 to 00-00-1996**

4. TITLE AND SUBTITLE **The JPL Hg+ Extended Linear Ion Trap Frequency Standard: Status, Stability, and Accuracy Prospects**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **California Institute of Technology,Jet Propulsion Laboratory,4800 Oak Grove Drive, MS 298-100,Pasadena,CA,91109**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADA419480. 28th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, Reston, VA, 3-5 Dec 1996

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

the DSN.[7] Ions confined in a trap allow for long interrogation times and high atomic line Q. Continuous operation is made practical using a ^{202}Hg lamp to generate 194.2 nm radiation for atomic state selection and a helium buffer gas for ion cooling.[8] The large 40.5 GHz $^2S_{1/2}(F=0,m_F=0)$ to $^2S_{1/2}(F=1,m_F=0)$ ground state hyperfine transition in mercury is less susceptible to magnetic and Doppler shifts than in transitions in lighter atoms, providing good long-term frequency stability with minimal environmental regulation. The linear ion trap provides a way to increase the detected fluorescence signal-to-noise ratio (S/N) without increasing the second order Doppler shift.[1] The ^{199}Hg+ hyperfine transition is typically interrogated using Ramsey successive oscillatory fields with two 0.4-second microwave pulses separated by an interrogation time ranging from of 1 to 30 seconds, depending on the local oscillator.

Presently achieved signal-to-noise and line Q with a LITS (Figure 1) imply a short-term frequency stability of $\sigma_y(\tau) = 2\times10^{-14}/\tau^{1/2}$.[7] A major challenge to realizing the full stability has been the stability of the local oscillator. To date, only a quartz VCXO or some hydrogen masers have had sufficient reliability to serve as LO's for trapped ion frequency standards in the DSN. In both cases the achievable frequency stability is compromised due to local oscillator frequency noise at multiples of the interrogation cycle frequency.[9] Liquid helium-cooled sapphire resonator technology provides stability that is sufficient to not degrade the LITS stability. Unfortunately the need to periodically fill a helium Dewar has limited the practicality of using cryogenic sapphire as a permanent local oscillator. A program at JPL has recently been initiated to develop a continuously operating Compensated Sapphire Oscillator (CSO) cooled with a closed cycle refrigerator to $\approx$10 K.[10] The frequency stability goal of 3×10^{-15} for 1 to 100 seconds will provide an ideal local oscillator for the LITS. The CSO/LITS combination will meet all radio science and gravity wave search frequency-stability needs in the DSN for the upcoming Cassini mission to Saturn. Figure 2 shows schematically the LITS short-term stability when operated with a quartz VCO or a hydrogen maser as the LO. Also shown is the projected stability when operated with the CSO under development and the LITS operating at $\sigma_y(\tau) = 2\times10^{-14}/\tau^{1/2}$.

The long-term stability (and potential accuracy) is fundamentally related to the size of sensitivity to environmental perturbations and the ability to know and control (measure) them. The three largest frequency offsets in present LITS operation[3] are: 1) the Second-Order Zeeman Shift (DC magnetic fields); 2) the Second-Order Doppler shift (due to thermal and driven ion motion); and 3) a pressure shift due to collisions with the helium buffer gas. In the LITS, the entire trap, UV optics systems, and Helmholtz coils are surrounded by five large nested magnetic shields. This magnetic shielding is sufficient to reduce external magnetic field fluctuations by 20,000, providing a fractional frequency sensitivity to external fluctuations of $\approx2\times10^{-17}$/mG. The trap/optics/shield region requires thermal regulation to only 0.1°C to achieve a frequency stability of 10^{-15}. Long-term stability requires the ion number/temperature to be stable over the length of the averaging interval. The ion number depends on several operating parameters, trap well depth, ion load and loss rate, and the condition of the vacuum. The vacuum system has a base pressure of $\approx1\times10^{-9}$ torr, a mercury background pressure of about $\approx5\times10^{-10}$ torr and a helium buffer gas pressure of $\approx10^{-5}$ torr. Mercury vapor is generated by heating a small sample of HgO to approximately 200°C, and helium is introduced through a heated quartz helium leak and stabilized to an ion gauge pressure measurement. Possible aging of the vacuum system, ion gauge, or changes in the Hg pressure as a function of HgO temperature over time are presently not controlled though the electron current used to ionize ^{199}Hg atoms and the temperature of the HgO source are regulated. The longest continuous stability measurement to date in this "open loop" operation is a 5-month comparison between an early research standard (LITS-2) and a cavity-tuned hydrogen maser.[4,5] Over this 5-month interval the relative long-term drift was measured to be 2.1 ($\pm$0.8)$\times10^{-16}$/day. Stability comparisons up to 1 month have been

performed between two LITS standards, with the flicker floor of the earliest LITS standards LITS-1 and LITS-2 measured at 5×10^{-16} at 100,000 seconds.[5] The source of this limit, though not completely resolved, apparently arises from variations of the ion number/temperature as a function of vacuum parameters which change slightly under environmental perturbations.

RECENT RESULTS WITH THE EXTENDED LINEAR ION TRAP STANDARD (LITE)

An extended version of the current LITS standards (often referred to as "LITE" or "Shuttle trap") provides several advantages to the current LITS scheme.[11,12] The LITE consists of two separate trap regions, a magnetically shielded region for microwave interrogation, and a separate region for ion loading and state preparation/detection using 194 nm light. Ions are "shuttled" back and forth between these two regions using only DC potentials. Practical advantages are that the LITE can be made much smaller (perhaps even for spaceflight[13,14]), more maintainable (because of improved access to lamp and photon detectors), and should offer reduced sensitivity to environmental perturbations. Performance advantages, especially towards further improvements of long-term stability and accuracy should result by operating at reduced ion densities during microwave interrogation. Therefore, the sensitivity to the portion of the second-order Doppler shift most difficult to keep stable (i.e. ion number fluctuation in the trapping RF field) is significantly reduced without reducing signal-to-noise or line Q. This long-term performance gain comes without further improvements to environmental regulation or compromising continuous reliable operation.

Figure 3 shows the 40.507 GHz signal resulting from Ramsey interrogation of ions in the first LITE trap. The resonant frequency measured represents the magnetically shielded hyperfine transition, though fluorescence detection actually occurred when the ions were subject to the earth's ambient magnetic field. The inferred performance in Figure 3 is $\sigma_y(\tau) = 5.9\times10^{-14}/\tau^{1/2}$, accomplished with an 11.1-second interrogation time and only a single detection system. With a second collection system a $\sqrt{2}$ improvement would give a performance of $4\times10^{-14}/\tau^{1/2}$, already within a factor of 2 of the best ever measured in a LITS. Figure 4 shows a 5-day stability comparison using a hydrogen maser as the local oscillator and an SAO hydrogen maser[15] as the reference. The performance shown indicates good intermediate-term stability between 20 and 20,000 seconds (the data shown for times less than 20 seconds are an artifact of the measurement technique). For comparison times longer than 20,000 seconds, the stability is most likely limited by drift in the maser. Longer-term comparisons to a LITS have yet to be done, though it is expected that the long-term stability of the LITE will be significantly better than the current LITS.

A new "shuttle" trap standard currently being developed in our laboratory solely for performance enhancements is shown in Figure 5. Significantly improved magnetic field homogeneity should allow operation at lower magnetic fields by a factor of nearly 8, reducing sensitivity to external and applied magnetic perturbations. The extended trap will have an interrogation region 7 times longer than in the present LITS, reducing sensitivity to all long-term systematics affected by ion number/temperature variations . In principle, this could reduce the flicker floor to $\approx1\times10^{-16}$ with corresponding improvements to long-term stability without additional environmental regulation.

Though there is still much stability and accuracy to be gained operating at room temperature, stability performance significantly below 10^{-16} will most likely require cold ions (and a superb LO). Unfortunately most ion-based microwave standards require ultraviolet light for optical pumping and/or laser cooling. While single laser-cooled ions may in principal provide the

highest accuracies[16], the need for stability and practical UV laser system currently makes the approach of direct laser-cooling and detection inappropriate for the DSN. An alternative approach, which may prove to be more practical, may be the possibility of using laser-cooled neutral atoms for state detection and cooling of trapped ions.[14]

CONCLUSION

A mercury linear ion trap frequency standard has been developed for continuous operation and tested in the NASA Deep Space Network. Measured signal-to-noise and atomic line Q indicate that a short-term stability performance of $\sigma_y(\tau) = 2\times10^{-14}/\tau^{1/2}$ can be achieved when operated with an appropriate local oscillator. Recent developments in sapphire resonator fabrication has resulted in an effort at JPL to develop a continuous operating Compensated Sapphire Oscillator (CSO). This oscillator when steered with the LITS should provide frequency stability around 10^{-15} from times ranging from 1 second to months.

Initial measurements taken with the first LITE (shuttle) standard show a short-term stability similar to the LITS. A stability measurement for 5 days indicated that the flicker floor is at least equivalent to the LITS with significant improvements to long-term stability expected. In a second generation "shuttle" trap currently under development, the flicker floor resulting from current environmental sensitivity may be reduced by a factor of 7. When operated with the CSO as a local oscillator very low flicker floors, perhaps breaking into the 10^{-17} region, should be possible for averaging times less than 100,000 seconds. Longer-term stability (and potential accuracy determination) should also be improved by the achievable sensitivity reduction. This would be accomplished using the same electronics as the LITS and the same low degree of environmental regulation.

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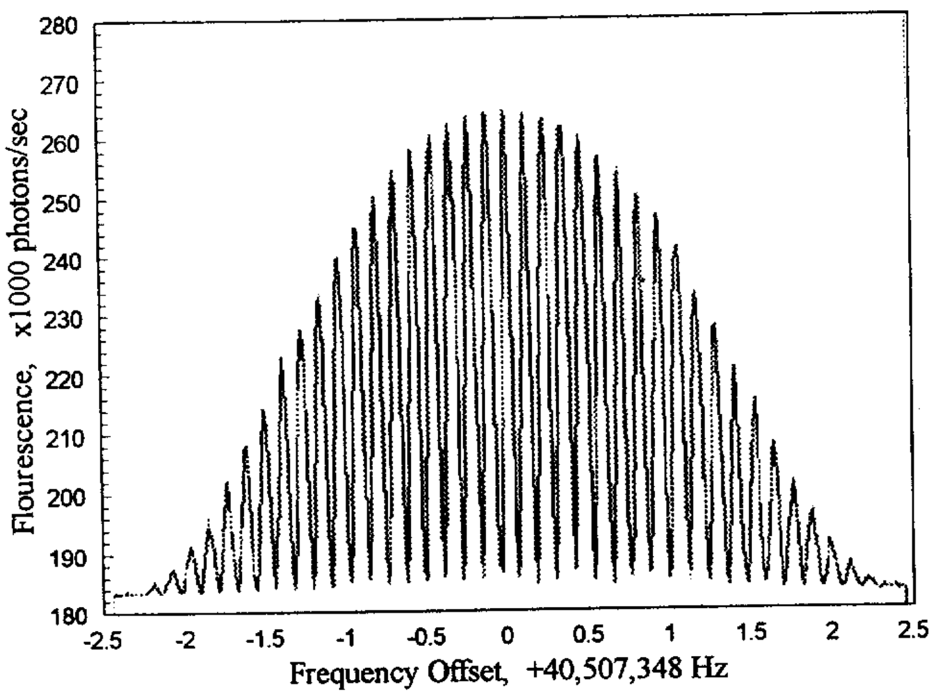

Figure 1: The 8 second Ramsey interrogation signal from the engineering prototype LITS-4 (cycle time 12 seconds). This signal to noise and line Q correspond to a stability of $2.0 \times 10^{-14}/\tau^{1/2}$

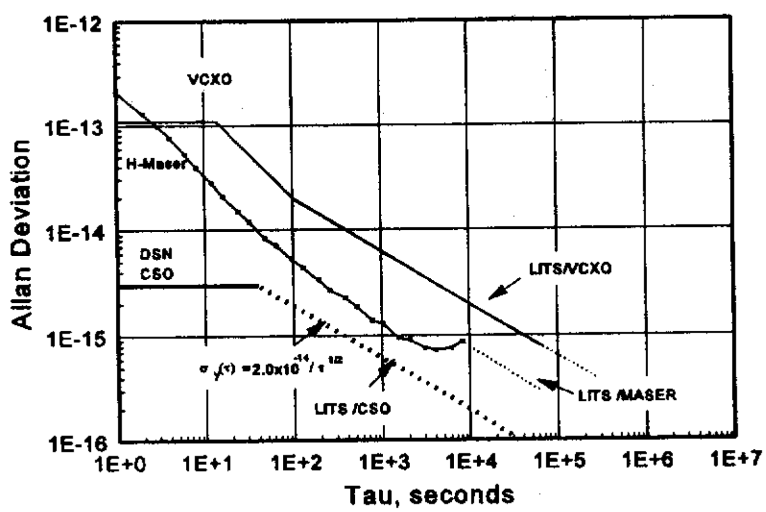

Figure 2: LITS performance shown using either a quartz VCO or a hydrogen maser as the local oscillator. Also shown is the expected performance with a continuously operating compensated sapphire oscillator under development and the LITS operating at $2.0 \times 10^{-14}/\tau^{1/2}$.

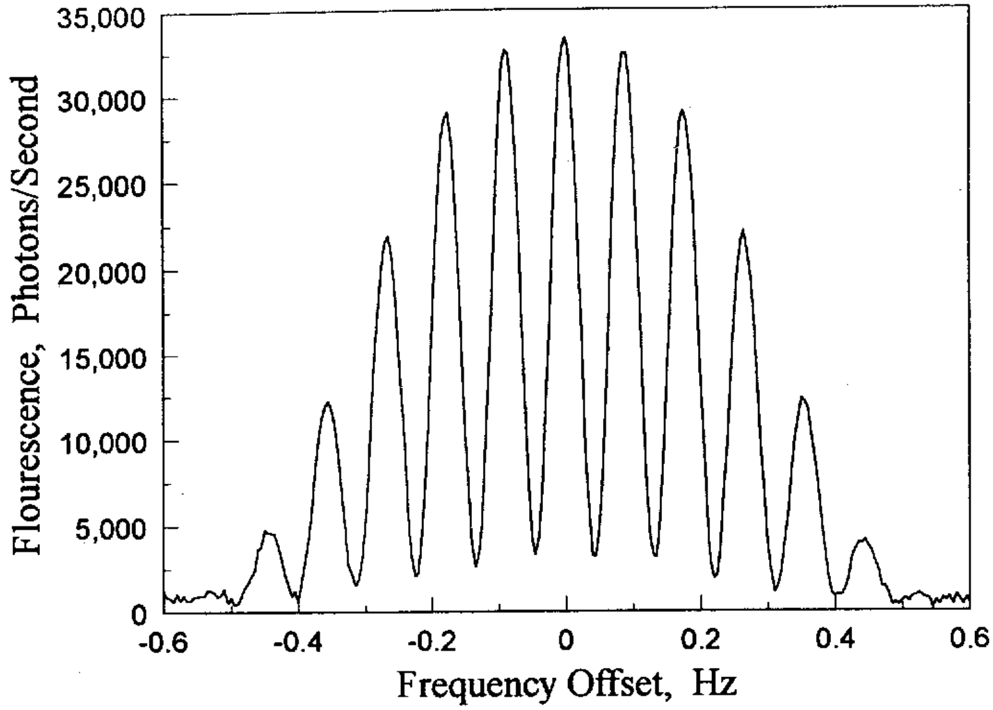

Figure 3: Ramsey interrogation fringes from 11.1 second interrogation cycle in the first LITE research standard.

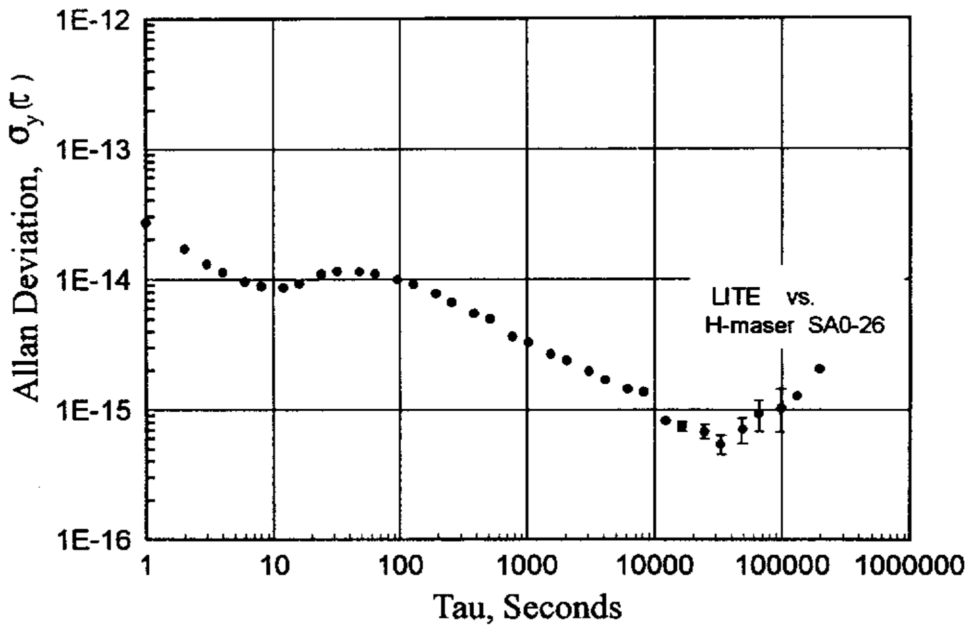

Figure 4: Five day frequency stability comparison of the first LITE research standard to the hydrogen maser SAO-26.

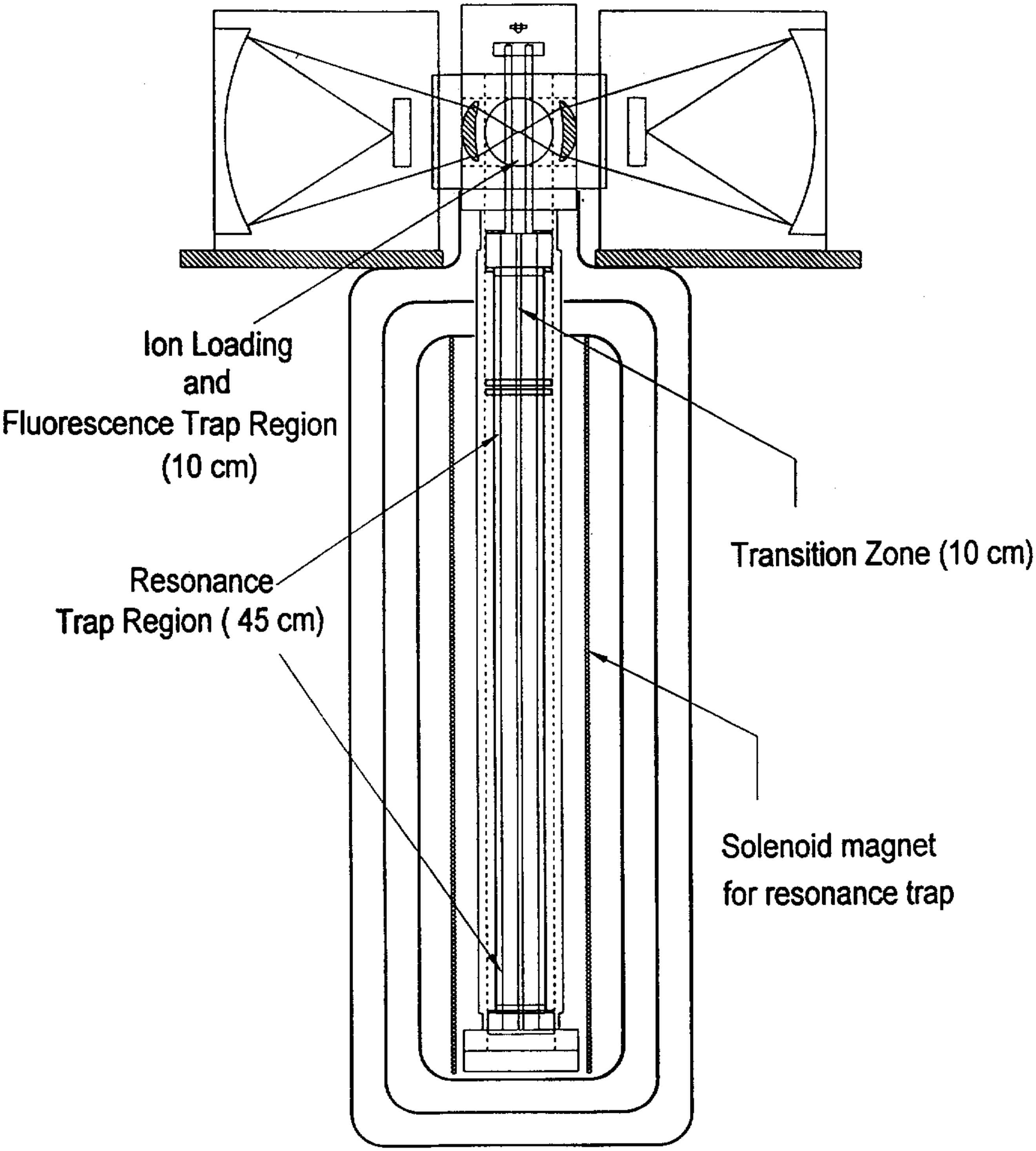

Figure 5: A scaled representation of the new "shuttle" trap incorporated into an existing LITS vacuum and optical system. The microwave resonance region is seven times longer than in the original LITS to reduce sensitivity to the Second-Order Doppler shift.

Questions and Answers

ANDREAS BAUCH (PTB, GERMANY): I understood that this local oscillator degradation comes about by the multiples of phase noise of the local oscillator, multiples of the modulation frequency.

ROBERT TJOELKER: That's correct.

ANDREAS BAUCH: If you do that at the multiples of your modulation frequency, the quartz in your maser will be the determining local oscillator, not the maser itself. Am I wrong? So I didn't understand why there can be such a large difference between locking it to the maser or to the quartz. What's your attack time in the maser?

ROBERT TJOELKER: The attack time in the maser is usually longer, first of all, because we take advantage of the high Q. So we run 8 to 16 seconds interrogation when we use a maser as a local oscillator; as opposed to the quartz, we must attack it much quicker, so we operate the quartz at about 3-second interrogation time.

ANDREAS BAUCH: Okay, there's a difference in the operation.

ROBERT TJOELKER: Yes, total performance difference isn't only the so-called Dick effect. There was also just a loop effect of getting the crystal down there as well.

ANDREAS BAUCH: You stated pressure dependence of the frequency is about 10 to the minus 13th per 10 to the minus 5th torr. If you have a 10 to the minus 13th frequency shift. How you can you stabilize this to one per mil?

ROBERT TJOELKER: That's the total offset; we operate at 10 to the minus 5th torr. An ion-gauged controller, that's the question on long-term stability, for example.

ANDREAS BAUCH: Yes, that's what I'm asking you.

ROBERT TJOELKER: Right. Certainly on the short term, they can do a part per thousand easily. For the very, very long term, there's, as far as I see it, two potential long-term aging mechanisms. I think a lot of the rest are going to be random systematics that are railed, for example; pressure and thermal sensitivities are railed, the way they would creep in. There would be aging of the ion-gauged control for the reference. Or there's the mercury pressure, which at the moment we run open loop. We just control the temperature on the mercury sample, which gives some baseline pressure. Over very, very long times, that could change.

There are ways of dealing with both, but at the moment we don't.

ANDREAS BAUCH: So you want to say the performance you have achieved is with commercial vacuum measurement equipment?

ROBERT TJOELKER: That's correct.

ANDREAS BAUCH: An active loop on the helium pressure?

ROBERT TJOELKER: That's right. It's a heated quartz leak that's servoed to an ion gauge controller.